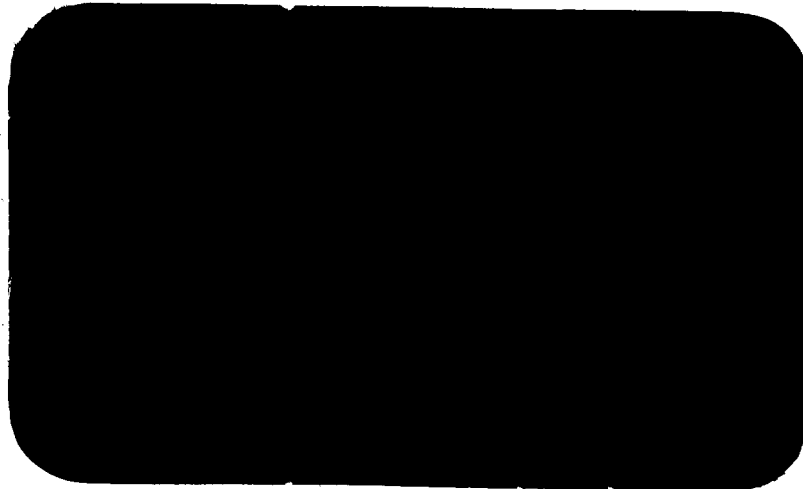


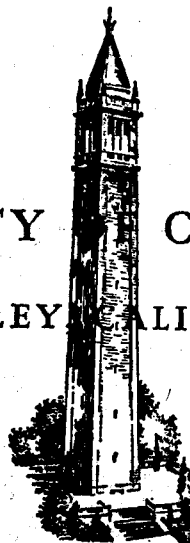
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<u>N66-15345</u> (ACCESSION NUMBER)	<u>1</u> (THRU)
<u>37</u> (PAGES)	<u>1</u> (CODE)
<u>CR 69289</u> (NASA CR OR TMX OR AD NUMBER)	<u>29</u> (CATEGORY)



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GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

Hard copy (HC) 2.00

Microfiche (MF) .50

Space Sciences Laboratory
University of California
Berkeley, California

Increased Brightness of the Lunar Surface

by

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Technical Report on

NsG 243-62

Series No. 6, Issue No. 35

June 15, 1965

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Abstract

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A number of mechanisms have been examined by which the enhanced solar radiation and flare protons could produce increases of the moon's brightness. The most plausible processes include direct luminescence, enhanced reflection in spectral regions characteristic of newly formed color centers, and indirect luminescence due to optical bleaching of these centers. However, the presumed solar energy flux intersecting the moon's orbit is not sufficiently intense for these processes to cause more than a fractional increase. Alternatively, the enhanced local brightness may have a solar origin. As more intense electromagnetic flux gives rise to a higher reflectivity in proportion to the color and intrinsic reflecting power of the surface material, existing color contrasts of the different lunar features become augmented.

Author

I. Introduction

Kopal and Rackham (1963) reported that lunar luminescence had been observed on November 2, 1963; they have attributed the increased brightness to stimulation by solar flare proton bombardment. However, the energy balance of the process requires a higher incident flux than that characteristic of a class 1 solar flare which has been related to this particular event. Moreover, laboratory experiments (Derham, 1964) indicate that the efficiency of the process is lower than the authors had originally assumed. In the present study the feasibility of alternative mechanisms is explored as brightening could be due to indirect luminescence and to enhanced reflectivity resulting from color centers that are produced in the surface material by the flare protons. For the purpose of clarification a brief discussion of the recent lunar observations given in Section 2, has been followed in Section 3 by a review of some general aspects of reflection and color center formation, largely the domain of solid state physics. The steps involved in calculating to an order of magnitude the relevant quantities are discussed in Section 4 and the relative significance and limitations of the hypothesized processes are recapitulated in Section 5.

Proton bombardment during periods of enhanced solar activity and solar electron bursts with energies up to 100 kev may constitute the excitation sources. A sudden passage of plasma clouds having above-normal particle densities might provide a flux sufficiently high to induce luminescence. It has been suggested that particle emissions, coincident with solar flares that produce geomagnetic storms are most likely to cause lunar brightening. The average time delay between slow-drift radio bursts and geomagnetic

storms is of the order of 33 hours, corresponding to a stream velocity of about 1250 km/sec. These low-energy charged particles, expelled from active solar centers, propagate in a radial direction with velocities of 1000-2000 km/sec in the form of plasma clouds having a density of 30 cm^{-3} or 100 cm^{-3} (Parker, 1964). Since lunar brightenings are rarer phenomena than geomagnetic storms such a simple correlation appears unlikely. According to Cameron (1964) protons and electrons may be accelerated in the distant geomagnetic tail and may therefore constitute another excitation source. Energies of protons and electrons corresponding to a given flux are shown in Table 1; they illustrate that the ranges that could possibly occur at the moon's orbit are several orders of magnitude less than are needed for luminescence (Flamm and Lingenfelter, 1965).

II. Observations

With concerted efforts and improved instrumentation available now, observations of increased lunar brightness may become less infrequent events than had been thought heretofore. This has been attested to already by the number of recent reports, summarized in Table 2. However, it is conjectural at this time whether these observations are replicas of changes in the solar radiation or whether they have a definite lunar origin, and in the latter case, if there is a common underlying cause. Kopal and Rackham (1964) were the first to relate intensified lunar brightness to a specific solar flare event. Of the two consecutive increases in brightness observed in the vicinity of the crater Kepler on November 1 and 2, 1963, the intensity of the latter event appeared to double within 15 minutes, a reaction rate that may be indicative of the mechanism. The ramifications of other observations

listed in Table 2 have been reviewed by Grainger and Ring (1962). To determine possible correlations between these observations and solar and geomagnetic activity, the appropriate data, obtained from the NBS-CRPL Bulletins, Series F, are presented in Table 3. The dates of lunar brightening are identified by arrows. From a comparison of these events, a trend relating lunar brightening with enhanced solar activity cannot be discerned, in contradiction to recent claims associating solar plasma flux with the brightness of the eclipsed moon (Matsushima, 1965).

It should be pointed out that increased brightness has always been attributed to luminescence of the surface material or to escaping residual vapors made to fluoresce by the action of solar electromagnetic radiation. Alternative mechanisms leading to an increase in the normal albedo are being examined here as possible causes for temporarily bright areas on the moon's disk.

The observed increase in relative brightness can be converted into absolute units by assuming an average albedo (Kozyrev, 1956)

$$A = \frac{\pi B_{\lambda}}{S_{\odot}}$$

where $S_{\odot} = 2.16 \times 10^{-5} \pi F_{\lambda}$; F_{λ} refers to the radiation of the sun's surface and the numerical factor is the geometrical dilution, $(R^2/4a^2)$, with R the solar radius and $a = 1 \text{ a.u.}$ The fractional increase, x , becomes then

$$B_a = x(\lambda) \pi B_{\lambda} = x(\lambda) S_{\odot} A$$

and the total energy emitted within an observed spectral region is given by

$$\int_{\lambda}^{\infty} B_a d\lambda = x(\lambda) S_{\odot} A.$$

However, there is considerable uncertainty in the value of the energy incident on the lunar surface since the reflected light depends critically on the efficiency of the process. From his observations in October, 1955, Kozyrev (1956) found a value of $1.6 \times 10^4 \text{ erg cm}^{-2} \text{ sec}^{-1}$ for the total emitted energy. By assuming $(A/n\eta) \approx (0.05/0.5 \times 0.1) = 1$, he estimated the corresponding solar flare proton density for $v = 1500 \text{ km/sec}$, from the relation $F = (1/2) mv^2 p_v$, to be about $5 \times 10^3/\text{cm}^3$. Such a high particle flux, invoked by Kozyrev (1956) and by Kopal and Rackham (1964) to interpret their observations, cannot be supplied by a single flare event, but may possibly be accumulated in a number of successive events, of originally distinct velocities, which coincide at the moon's distance from the sun during brief periods of time. Alternatively, increases in lunar brightening probably follow a complex set of events including the passage of plasma clouds stored in interplanetary space (Anand et al. 1964). But unless the input energy is sufficiently large, lunar luminescence cannot arise from the solid surface material, as will be discussed subsequently.

The recent lunar observations have occasioned renewed laboratory luminescence studies of materials likely to occur on the moon's surface. Greenman (1963) suggests that among the minerals tested quartz, orthoclase (K-feldspar), and enstatite (MgSiO_3) could account for lunar luminescence, although noting that some variations in brightness among the surface features may be due to different porosity and state of aggregation rather than to different compositions of material. Derham et al. (1964) extended earlier studies and found that the luminescence of "Buster" meteorite dust, when excited by protons in the range of 5 - 100 keV, is proportional to the applied voltage and beam current (in the μ amp range) and has an efficiency of about

1 per cent. By means of UV excitation (2537 Å), the efficiency has been observed to drop to 0.01 per cent and the resulting luminescence no longer showed any spectral structure. Reid et al. (1964) also compared the luminescence properties of a large number of terrestrial minerals, as did Nash (1965).

The laboratory experiments designed to explain the observed lunar brightening require a higher flux than that prevailing at the moon's orbit, according to present-day knowledge. This suggests that either the lunar sphere is exposed to sporadic radiation more intense than that extrapolated from terrestrial and space probe experiments, if the observations listed in Table 2 and earlier ones reported by Link (1946) and Dubois (1956) have a true lunar origin, or the observed increases have a solar origin. In this connection Kopal (1965) pointed out that Zodiacal light also displays intermittent intensification; this suggests that lunar brightening and Zodiacal light may have a common solar origin, a possible explanation that merits closer examination.

III. General Considerations

In this section the limitations of luminescence mechanisms as observed in the laboratory are examined. Several of these processes could account for increases in the lunar brightness provided the excitation sources were of sufficiently high energy; however, the present observational data of quiet solar radiation and solar flares indicate that high-energy events in the vicinity of the earth have a low probability of occurrence, providing ample reason for a normally non-luminescing moon. Before considering lunar brightening specifically, general aspects of luminescence and electron transitions associated with color centers are reviewed briefly.

1. Color Centers

The production of color centers, not invoked heretofore to explain lunar brightening, could take place during periods of enhanced solar activity. Although the principal studies of color centers have been concerned with ionic crystals of the alkali halide type, covalent systems like quartz, numerous silicates, and alkaline earth oxides have been examined to some extent. A color center refers to a particular electronic configuration which gives rise to optical absorption in an otherwise transparent spectral region. Upon irradiation and particle bombardment, lattice defects are produced that act as trapping centers for electrons undergoing transitions from the filled valence bands. The crystal defects comprise cation and anion vacancies, interstitial atoms, dislocations or isolated impurities such as H, C, O, or N atoms, while Mn, Cr, and Fe ions are frequently encountered in minerals. Energetic photons act indirectly by producing photoelectrons which in turn cause atom displacements.

A number of different type of color centers with distinct electronic configurations have been identified, but the most prominent is the F center; it is attributed to an electron trapped in the field of an anion vacancy. Trapped hole centers (deficient in electrons) are associated with V_2 and V_3 centers; they are generated in the valence band due to an electronic transition into the conduction band or energy gap. However, V centers are not as stable as F centers and decay rapidly at room temperature. Other types of color centers like R_1 , R_2 , and M, which also give rise to characteristic absorption bands in the usually transparent spectral region, are readily thermalized and transformed into F centers. Several empirical rules of the general form $\lambda_{\max} = C_d^n$ have been established,

relating the spectral absorption peak to the distance d between nearest neighbors in the crystal lattice. A scale showing the approximate spectral location of these color centers is given in Fig. 1 and the electron distribution in insulators is illustrated in Fig. 2. The forbidden energy gap is about 10 eV depending upon the nature of the material. The lattice representation of color centers is schematically depicted in Fig. 3. Since the absorptive properties of the crystals are related to their reflectivity, the quantity most decisive in the brightness of the moon's surface, brief reference to Smakula's equation (Dexter, 1956) should be made. It relates the number of color centers in the crystal to the absorption intensity

$$N f = c \int k(E_{\nu}) dE_{\nu}$$

$$= 0.87 \times 10^{17} \frac{n}{(n^2 + 2)^2} k_{\max} H$$

where k_{\max} , H and f designate the absorption coefficient (cm^{-1}), the half-width, and oscillator strength, respectively. This equation permits the determination of the concentration of color centers from the optical density of the material; by this method saturation values have been found to be of the order of 10^{18} to 10^{19} color centers cm^{-3} . At low temperature an exponential build-up of color centers occurs and at higher temperatures (room temperature and higher) saturation follows a second order recovery process.

The energy necessary for the formation of color centers is difficult to estimate because it depends upon the previous history of the crystal and the temperature during irradiation. If many defects exist already in the crystals, as in the case of natural materials, energy is required principally

to excite electrons into the existing trapping centers. The energy needed to generate vacancies and to capture electrons is by a factor of 40 larger than that for the capture process alone. While a basic mechanism of color center formation applies generally, the conditions for particular crystals are highly specific. It may be of interest to cite some examples illustrating the limitations and hence the possible applicability to lunar conditions. By means of x-rays in the 10-60 kev range and by γ - rays in the Mev range color centers are introduced, yielding a coloration comparable to that attained by the bombardment with electrons. Since x-rays are absorbed close to the surface, highly colored surface layers can be produced, in contrast to γ - rays which penetrate into the crystal lattice. However, the high flux of x-rays requiring one hour exposure at some 20 ma under laboratory conditions obviates the consideration of this process as a likely one to occur on the lunar surface.

The production of color centers by proton bombardment, of most interest in this study, has not been investigated extensively heretofore (Grannis, 1961). A number of projects referred to in Section 2 have been initiated recently to relate the composition of lunar type rocks to their luminescence in the search for an explanation of increases in lunar brightness.

Since the lunar surface material is likely to be comprised of some type of siliceous material, a brief discussion of the production of color centers in quartz appears relevant. The principal defects result from the rupture of Si-O bonds followed by the formation of oxygen vacancies and interstitials and networks of O_2 or possibly of O_2^+ . Silicon vacancies are less likely to occur because of their greater bonding strength. Although

the resulting absorption peaks are characteristic of the impurity atoms present, a maximum color center concentration of $10^{18} - 10^{19} \text{ cm}^{-3}$ is generally attained by x-ray irradiation or by particle bombardment. The threshold incident flux is of the order of 10^{12} nvt , but in the majority of laboratory experiments a flux of $10^{15} - 10^{17} \text{ nvt}$ has been employed.

Absorption bands in the spectral region near 6200 \AA (C center), 4500 \AA (A_1 center) and an intense band near 2000 \AA have been observed. A-type bands are identified with a substitutional Al atom which has captured a hole and the C-bands with an electron trapped at an O-vacancy. Another intense band at about 1650 \AA has been ascribed to a positive hole trapped at an interstitial O^{-2} .

As stated above, these color centers may be of mere academic interest since the F center is most prominent. Moreover, the defects existing in all minerals are largely dependent upon the type and concentration of the impurity atoms present. Consequently, the lunar surface material is not likely to be identifiable with specific minerals on the basis of direct or indirect luminescence. At best, the production of color centers may represent a possible mechanism that could account for a fractional increase in the average lunar brightness.

2. Lunar Albedo and the Complex Refractive Index

The lunar surface reflects the incident solar light in proportion to its intrinsic reflectivity, but if this reflectivity is increased by the introduction of color centers, then for the same incident radiation, the reflected light will be intensified. This is one of the mechanisms suggested here. Since the enhanced lunar brightness is thereby related directly to the change

in the effective albedo, its characteristics are reviewed briefly. The coefficient of diffuse reflection, the albedo, defined as the ratio of the reflected to the incident light, depends upon the wavelength of illumination and the angle of incidence i . The albedo or coefficient of brightness, $A' = B/B_0$, is usually referred to a standard surface having unit brightness under identical conditions of illumination. Since the brightness is also a function of the phase angle, α , the total reflecting power which is independent of the condition of illumination, the spherical albedo, is introduced. It is defined as the ratio of light reflected in all directions to that incident upon the surface. According to the Russell-Bond definition, the spherical albedo is

$$A = \frac{I_m}{I_s r} 2 \int_0^\pi f(\alpha) \sin \alpha d\alpha,$$

usually written in abbreviated form, $A = p q$, where $p = I_m/I_s r$ denotes the geometrical or normal albedo with I_m , I_s , and r designating the integral brightness of the moon and of the sun and the angular radius of the moon in radians, respectively. The symbol q refers to the phase integral or photometric function. Alternatively, A may be written as

$$A = \pi R(i, e, \alpha) = R_0 f(i, e, \alpha),$$

where R_0 is the normal reflectivity, the quantity germane to the proposed mechanism for the enhanced lunar brightness. Upon normalizing $f(i, e, \alpha)$ by setting $f(0, 0, 0) = 1$ for $i = e$, R_0 then represents the normal albedo. Although the lunar albedo appears to be independent of wavelength, differences between individual features exist, ranging from a low value of 0.054 for dark, smooth areas like Sinus Medii, 0.18 for crater Aristarchus to a maximum of 0.31 for the rough veneer of Tycho (Gehrels et al. 1964).

For dielectric materials possessing selective spectral absorption, R_o is identified with the Fresnel reflection coefficient given in terms of the complex refractive index

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}.$$

It increases with decreasing refractive index, n , and with increasing extinction coefficient, k , related to the absorption coefficient by $k = 4\pi a/\lambda$. Under the usual conditions of illumination the normal albedo of the lunar disk is a monotonic function of wavelength, showing an increase from the ultraviolet toward the infrared spectral region. If absorbing centers are present, anomalous dispersion will occur as described in the following Section and the resulting reflectivity will no longer be a uniform function of wavelength. In the present approximation the selective absorption has been accounted for by a simple change in R_o . However, this is an obvious oversimplification because the scattering by centers, each of which possesses enhanced reflectivity, gives rise to a nonlinear increase in the apparent albedo as higher powers of R may contribute to the effective albedo; for a given photometric function, an increase in brightness may perhaps be related to an increase in the normal albedo such that

$$\Delta A \approx R^n f(i, e, \alpha).$$

Assuming the photometric function to be independent of wavelength Rougier has found a value of 0.58. Efforts are still being made (Hapke, 1963) to find a unique analytical photometric function that reproduces the characteristic shadow effects of the innumerable minute surface details. In our model calculation the exact form of this function is not critical since any

change observed in the reflected light intensity has been related directly to the change in the effective normal albedo of the minerals in a given area without regard to the scattering property determined by the geometry of the surface layer.

The nonlinear effect of changes in the refractive index on the surface reflectivity suggests that such a mechanism might contribute to variations in lunar brightness. The following set of values illustrates the relative changes in the reflectivity R for a given change in the refractive index n :

<u>n</u>	<u>n%</u>	<u>R%</u>
1.4	1	6
1.4	10	63
1.4	20	132
1.65	8	46
1.84	6	22

It should be noted that particle bombardment can also result in a decrease in the reflection coefficient by altering the surface layer up to a depth of 0.1μ (Hines, 1960). However, the extent to which these effects need to be taken into account in any theory of lunar brightening remains uncertain.

3. Luminescence

a. Direct Luminescence

Both irradiation and particle bombardment can cause luminescence in photosensitive minerals provided the excited state of the lattice atom is sufficiently short-lived to permit a radiative transition to occur. Radiationless transitions in which the incident energy is dissipated by lattice vibrations compete effectively at elevated temperatures. Any lattice defects, essential to the production of color centers as has been discussed

above, provide sites for radiationless transitions and account in part for the observed low efficiencies. According to Garlick (1958) if L_0 denotes the luminescence intensity in the absence of defects ($c=0$),

$$L = L_0 (1 + kc)^{-1}$$

where the fraction of damaged to undamaged constituents is given by

$$c = \exp\left(\frac{NZ}{N_0} - 1\right) \approx \frac{NZ}{N_0}$$

when the damage is small, with N_0 , N , and Z denoting the total number of bombarding particles, the number density of the crystal, and the number of damaged units, respectively.

In contrast to particle bombardment whose principal effect is the displacement of lattice atoms, electromagnetic radiation causes primarily ionization. In the case of x-ray irradiation, secondary electrons give rise to luminescence. Representative systems are cited by Przibram (1956). If n_0 represents the incident x-ray photons ($0.5 - 1.5 \text{ \AA}$) the number of absorbed quanta is given by

$$dn = n_0 [\exp(-\mu x)] \mu dx$$

in a layer of thickness dx with μ being the absorption coefficient. The resulting luminescence is then determined by n , μ , and δ , the absorption coefficient for the emitted radiation within a layer of material D ,

$$L = \int_0^D n_0 \exp(-\mu x) \exp(-\delta x) dx$$

or

$$L = \frac{\gamma \mu n_0}{\mu + \delta} \left[1 - \exp(-(\mu + \delta) D) \right].$$

The efficiency for x-ray induced luminescence depends largely upon the effectiveness with which photoelectrons are produced (Curie, 1963). Many crystals possess a high efficiency for optical excitation but a low efficiency for particle bombardment. In the case of electrons having above-threshold values of 0.1 kev up to 1 kev, efficiencies as high as 10 per cent have been observed. Direct luminescence stimulated by proton bombardment is rather inefficient, ranging from a maximum of 10 per cent to around 0.01 per cent.

b. Indirect Luminescence or Radiophotoluminescence

Increases in lunar brightness might be generated by an indirect process in which the normal solar radiation and the enhanced flux act additively. Once color centers are produced on the sunlit surface in a manner described above, the UV radiation causes bleaching and photoemission with the usual Stokes shift of $\Delta E(\text{emitted}) \approx 1/2 \Delta E(\text{absorbed})$. Although this secondary radiation is directly proportional to the number of color centers formed, as in the case of direct luminescence, the efficiency may be 1 at low temperature, but more likely it is 0.01 near 100°C. This would explain the absence of lunar luminescence, even in the presence of unattenuated solar radiation.

IV. Calculations

1. Production of Color Centers

The bombardment by moderately energetic protons may produce color centers in the minerals on the lunar surface. While the maximum energy transferred is independent of the nature of the interaction, the distribution of the energy is not. According to Billington and Crawford (1961) this dependence is expressed in terms of the collision cross-section,

$$d\sigma(E, E_p) = K(E, E_p) dE_p$$

where the energy transferred to the stationary atom exceeds the displacement energy $E_p > E_d$. For a given integrated incident flux $\phi(E) = nvt$, the number of primaries or knock-on atoms per unit energy is given by

$$N(E_p) = N_A \phi(E) K(E, E_p)$$

where N_A denotes the lattice atoms per unit volume. If the incident radiation has an energy distribution,

$$N(E_p) = N_A \int \phi(E) K(E, E_p) dE.$$

In terms of $W_d(E, E_p)$, which defines the probability per unit energy that for a collision the primary energy will be E_p ,

$$N(E_p) = N_A \int \phi(E) \sigma_d W_d(E, E_p) dE.$$

When higher order collisions are taken into account the total number of displacements is then given by

$$N_d = N_A \sigma_d \phi \bar{\nu}$$

where the mean number of displaced atoms per primary knock-on, $\bar{\nu} \approx \bar{E}_p / 2E_d$.

The critical quantity σ_d has been variously approximated; in general,

$$\sigma_d = C \left(\frac{1}{E_d} - \frac{1}{E_{\max}} \right)^{-1}.$$

For particles in the high energy range (2-20 Mev), the screening of the nuclei by the outer electrons is neglected, so that for

Rutherford collisions the differential cross-section for the transfer of E to

$E + dE$ is given by

$$d\sigma = C \frac{dE}{E^2}$$

with $C = 4 \pi a_o^2 \left(\frac{m_1}{m_2} \right) z_1^2 z_2^2 E_R^2 / E_p$ and E_R denoting the Rydberg energy (13.61 eV). For low-energy particles the hard-sphere model is more appropriate as the interaction distance $R > a$ where $a = a_o (z_1^{2/3} + z_2^{2/3})^{-1/2}$ in terms of the Bohr radius a_o . The minimum distance R is determined by the screening action of the outer electron cloud. Then

$$d\sigma = C^1 dE$$

with $C^1 = \pi a^2 / E_{\max}$.

In calculating the values shown in Table 4, it has been assumed that (1) there is a simple displacement threshold, (2) the displacements arise from uncorrelated two-body collisions, (3) isolated interstitial atom-vacancy pairs are produced, and (4) these defects are identified with color centers of the type described in the preceding Section. A simple mono-energetic beam of protons has been considered to collide with the atoms in a quartz lattice. The approximate values indicate that the incident flux has to be fairly high to attain even a low level of coloration, that is 10^{16} to 10^{18} $N \text{ cm}^{-3} \text{ sec}^{-1}$. Assuming that the life-time of the color centers $\tau < t$, the duration of the incident flux, the cumulative effect of a prolonged flare results in the build up of color centers such that

$$N_d = \frac{dN_d}{dt} \left[1 - \exp \left(-\frac{t}{\tau} \right) \right] t$$

becomes

$$N_d = \frac{dN_d}{dt} t.$$

2. Increased Reflectivity

Color centers associated with selective absorption cause anomalous dispersion because enhanced reflectivity occurs in the absorption region. If the absorption band is weak the reflection minimum appears on the high frequency side of the absorption peak and the maximum on the low frequency side, but for a strongly absorbing center the maximum reflection is displaced toward lower frequency. Although for rough surfaces the relations no longer apply, the reflectivity is intensified in the general region of the absorption band. Hence, the change in reflectivity due to the newly formed color centers can be approximated by the well-known dispersion equation for a dielectric medium (Ditchburn, 1963),

$$n^2 = n_o^2 + \frac{4\pi Ne^2}{m} \frac{f}{w_o^2 - w^2 + i\delta w}$$

which for a small range about w_o ($w \sim w_o$) becomes

$$n^2 = n_o^2 + \frac{4\pi Ne^2}{mw_o} \frac{f}{2(w_o - w) + i\delta}$$

Since $n = n_o (1 - ik)$, where k is the extinction coefficient, the real and imaginary parts can be evaluated separately. It then follows that

$$n^2_k = \frac{2\pi Ne^2}{mw_o} \frac{f}{4(w_o - w)^2 + \delta^2}$$

and

$$n = n_o + \frac{4\pi Ne^2}{n_o mw_o} \frac{f(w_o - w)}{4(w_o - w)^2 + \delta^2}$$

Substituting appropriate values for four spectral regions and for a range of color center concentrations commonly observed in the laboratory, the refractive indices and extinction coefficients are computed and employed

in the determination of the reflectivity coefficients presented in Table 5. These values may be unrealistic since efficiencies varying from 0.04 - 0.1 have not been taken into account. However, if proton bombardment were to have cumulative effects, the low efficiency might be partially offset.

Since the computed values can be but suggestive of the actual process, it appears instructive to compare them with some experimental data. Upon proton bombardment of MgO an increase in the refractive index was noted with a simultaneous strong absorption in the 2000 - 3000 Å region (Primak and Luthra, 1965). Vitreous silica has also been observed to show a change in refractive index of 0.8% upon exposure to a neutron flux of $10^{21} \text{ cm}^{-2} \text{ sec}^{-1}$ in the 0.1 - 1 Mev range. While this small change causes a 3 per cent change in the reflectivity, in quartz under similar conditions a decrease of 5.6 per cent in its refractive index has been observed (Primak et al. 1955).

3. Luminescence

While direct luminescence is not likely to contribute to an increase in lunar brightness, indirect luminescence may, according to the following rough estimates. Assuming that the number of lattice defects, assumed to be identical with the number of color centers produced by proton bombardment, are given by

$$N_d = N_A \sigma_d \phi \bar{\nu}$$

in the above notation, then upon substituting appropriate values

$$N_A = 10^{21}, \sigma_d = 3 \times 10^{-16}, \phi = nv = 5 \times 10^{11} \text{ and } \bar{\nu} = 6, N_d = 10^{18} \text{ cm}^{-3}.$$

We also assume that the number of photons equals the number of color centers produced and that the photons emitted within one wavelength

(6700 \AA , for instance) of the surface layer can be observed, then the number of photons, $n = 6.7 \times 10^{13}$, which corresponds to an energy of $P = hn\nu = 8 \times 10^3 \text{ erg cm}^{-2} \text{ sec}^{-1}$ for an energy input of $10^5 \text{ erg cm}^{-2} \text{ sec}^{-1}$, with an efficiency of 0.08. Lattice defects are not likely to be introduced by electrons and x-rays because of their small collision cross-section; to be effective they require energies in the Mev range. Once color centers are produced by the bombardment of the surface material, thermal annealing is unlikely because of the low rate factor, being about 1 degree/hour. The energies obtained by indirect luminescence or radiophoto luminescence represent upper limits since radiationless transitions have a high probability at the temperatures prevailing on the sunlit surface of the moon.

V. Discussion

The results of our rough calculations cast serious doubt on the reality of lunar luminescence, in accord with the recent literature (Kopal 1965; Flamm et al. 1965; Anand et al. 1964); the principally unfavorable factors are the level of the radiation environment and the low efficiencies of the luminescence mechanisms. Moreover, the accumulation of iron meteorites would further reduce the chance for any photoemission to occur. As a corollary it follows that luminescence measurements will not be useful for in-situ identification of the surface minerals or the rock types. At best, the information will be comparable to that derivable from refractive indices which are characteristic merely of the types of crystals containing such compounds as SiO_2 , MgO , Al_2O_3 , Na_2O , and K_2O (Anderson and Schreiber, 1965). The non-specific response to the incident radiation arises from the effects of the small particle size, the complex geometry

of the surface layer, and the presence of impurity atoms. Indirect luminescence, or radiophotoluminescence, could take place concurrently with enhancement in reflectivity due to color centers produced by solar flare protons. While these processes may account for a small increase in lunar brightness, perhaps of the order of 10 - 30 per cent as shown by the data in Table 5, the efficiency is too low to effect a twofold intensification. Therefore, a solar origin appears most probable unless, for as yet undetermined reason, the solar radiation and plasma should be more intense than those extrapolated from terrestrial and satellite observations.

Since extensive mineral differentiation has probably taken place during the formation of the moon, the surface assumed a heterogeneous appearance. While prolonged solar radiation must have attenuated color differences, the infall of meteorites partially counteracted this radiation damage by dislodging particles upon puncturing the surface, thereby exposing undamaged material. Hence, during periods of increased UV and visible radiation, likely to attend solar flares, the persistent differences in reflecting power of the various minerals in local areas should become more pronounced and result in greater contrasts of the surface features. These might then explain the non-uniform localized lunar brightening, without any need to invoke photoemission processes. An extension of photometric models by incorporating the spectral dependence of the albedo should clarify the problem of enhanced surface contrasts as a function of wavelength.

The photometric models of the surface as determined by Hapke (1963) and by Gehrels et al. (1964) suggest that the sporadic brightening of the lunar surface might not be unlike that from the Zodiacal dust cloud, referred to below. Hapke inferred that the dust particles comprise only

10 per cent by volume of the surface layer, the remainder being interconnected vacancies, while Gehrels et al. (1964) conclude that positively charged interplanetary dust grains could form a 0.06 mm thick surface layer. The results of both investigations indicate that a highly perforated microstructure accords best with the observational data. This particulate, loose arrangement may be comparable to the aggregation of dust in the Zodiacal cloud, and therefore a common mechanism may underly the light scattering from the lunar surface, the Zodiacal dust cloud, the asteroids, and perhaps that from the noctilucent clouds.

The absence of observational patrols of Zodiacal light or lunar brightness precludes a direct comparison and reliable correlation with solar activity. However, as in the case of lunar brightening, striking increases of the Zodiacal light have been noted on February 25, 26, and March 2, 1943 by Dauvillier (1961) and on July 8 - 9, 1958 by Blackwell and Ingham (1961). The latter authors also exclude fluorescence as a possible explanation of the observed intensification. In view of the role which interplanetary dust particles play in all the above mentioned phenomena, increases in brightness may be accounted for in terms of a basically similar mechanism.

Acknowledgment

We wish to thank Professor W.J. Welch for reading the manuscript and Professor S. Silver for his interest and encouragement.

TABLE 1. Velocities and Energies of Protons or Electrons Providing a Given Energy Flux

Flux ergs cm ⁻² sec ⁻¹	Protons			Electrons		
	Velocity 10 ² km sec ⁻¹	Energy N = 10 cm ⁻³ kev	Transit Time (S-M) hours	Velocity 10 ³ km sec ⁻¹	Energy N = 10 cm ⁻³ kev	Velocity 10 ³ km sec ⁻¹ N = 10 ³ cm ⁻³ Energy ev
2	6	2	67	7.6	0.16	1.6 7.6
5.6	8.7	4	48	11	0.33	2.3 15
7.8	9.8	5	42	12	0.41	2.6 19
16	12	8	33	15	0.66	3.3 30
22	14	10	30	17	0.81	3.6 38
41	17	15	24	21	1.2	4.5 57
63	20	20	21	24	1.6	5.2 76
88	22	25	19	27	2.0	5.8 95
110	24	30	17	29	2.4	6.2 110
180	28	40	15	34	3.3	7.3 153
250	31	50	13	38	4.1	8.2 191
700	44	100	9.4	54	8.2	11 379

TABLE 2. Increased Brightness on the Lunar Surface

Date, U.T	Area	Spectral Range λ in Å	ΔB %	Method	Authors' Interpretation	Authors*
11/1/63 22.35-.42	Kepler	6725	100	Photographic; narrow band-pass interference filters	Luminescence of stony meteoritic material	K. and R. 1964
10/30/63 01.35-2.05	Aristarchus Schröter Valley	6200-7500	obscurations of surface details	photographic; color filters	luminescence from escaping gases	J.A.G. 1963
9/16/62 08.10 08.31	general	3934(K) and 3968(H)	13	photographic; line depth	luminescence	H. S. 1964
10/23/59 02.10-02.25	Alphonsus	5184-5900	altered appearance 40	photographic; line depth	luminescence	N.A.K. 1962
11/3/58 03.00-03.30	Alphonsus	4200-4750 and 5165-5635	15-20	photographic; line depth	fluorescence of escaping gases	N.A.K. 1959
11/17,18,19 & 12/19/56; 2/15,16/57; 11/1 & 12/2,3/1958; 1/25/59	Average of Maria and Craters	3300, 3600 4400, 4500 5400, 5600 6900 and 9400	10-20	UV and UGI photometry	radiative recombination of accreted interplanetary ion cloud above the surface	G.C. and O. 1964
10/26/56 20.00-21.00	Alphonsus	4200-4800	obscurations in blue spectral region of rill on crater floor	blue and red sensitized plates with pyrex filter	possibly due to escaping gases	D. A. 1957
10/4/55 22.00 10/28/55 18.30	Aristarchus, Rays of Herodotus	3934(K) and 3948(H)	13(H), 19(K) 2(H), 3.3(K)	photographic; line depth	luminescence of surface rocks	N.A.K. 1956

*References given on following page.

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References pertaining to Table 2.

- | | |
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| J.A.G. | J. A. Greenacre, <i>Sky and Telescope</i> , <u>26</u> , 316 (1963). |
| H. S. | H. Spinrad, <i>Icarus</i> <u>3</u> , 500 (1964). |
| N.A.K. | N. A. Kozyrev, <i>Publ. Crim. Astrophys. Obs.</i> <u>16</u> , 148 (1956). |
| N.A.K. | N. A. Kozyrev, <i>Sky and Telescope</i> <u>18</u> , 184 (1959);
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| G.C. and O. | T. Gehrels, T. Coffeen and D. Owings, <i>Astron. J.</i> <u>69</u> ,
826 (1964). |
| D. A. | D. Alter, <i>Publ. Astron. Soc. Pacific</i> <u>69</u> , 158 (1957). |
| N.A.K. | N. A. Kozyrev, in <i>Physics and Astronomy of the Moon</i> ,
ed. Z. Kopal, Academic Press, New York (1962), p. 375. |

TABLE 3. Solar Activity and Geomagnetic Kp Index Related Chronologically
to Lunar Brightening

Date	Solar Number	Flares class	Radio- bursts	ΣK_p	Date	Solar Number	Flares class	Radio- bursts	ΣK_p
10:28:63	8	1,2	III	11	10:30:58	9	1	I	27
29	13	1	---	37	31	6	1,2	I,III	21
→ 30	4	1	III	25	→ 11: 1	2	1	I	15
31	--	--	---	12	2	7	1	I,III	20
→ 11: 1	5	1,2	---	17	→ 3	6	1,2	I,III	20
→ 2	2	1	III	23					
			cont.		2:13:57	2	1,2	I,III	37
9:13:62	15	1	III	28	14	1	1	I	14
14	12	1	---	19	→ 15	-		II	19
15	12	1	cont.	23	→ 16	-		II,III	15
→ 16	6	1	cont.	18					
					12:16:56	2	1,2	----	6
11:23:61	6	1	---	3	17	8	1,2,3	II,III	6
24	--		---	5	18	15	1,2	II,III	11
25	--		---	9	→ 19	4	1,2	II,III	9
→ 26	1	1	---	10					
27	--		---	8	11:14:56	5	1,2	II,III	41
→ 28	--		---	5	15	3	1,2	I	45
29	--		III	6	16	2	1	II	36
30	3	1,2	---	4	→ 17	6	1	I,III	24
12: 1	--		---	35	→ 18	-		III	23
2	2	1	---	44	→ 19	4	1	II,III	9
→ 3	4	1	---	40					
					10:23:56	3	1,2	---	24
10:20:59	4	1	III	13	24	1	1	---	12
21	3	1,2	II,III	11	25	2	1	---	7
22	2	1	III	27	→ 26	1	1	I,II,III	33
→ 23	1	1	III	15					
					10:25:55	--		II,III	21
1:22:59	3	1	II,III	14	26	--		III	23
23	6	1	II,III	15	27	--		IV	22
24	5	1	II,III	8	→ 28	--		---	16
→ 25	10	1,2	II	22					
					10: 1:55	2	1,2	II,III,IV	42
11:30:58	14	1,2	I,III	3	2	1	1	III,IV	36
12: 1	18	1	I,III	4	3	1	1	II	20
→ 2	12	1	I,III	26	→ 4	4	1,2	III,IV	14
→ 3	15	1,2	I	12					

TABLE 4. Number of Color Centers Produced by Proton Bombardment

Velocity km sec ⁻¹	100 cm ⁻³	500 cm ⁻³	1000 cm ⁻³
1000	2 ^{16*}	1 ¹⁷	2 ¹⁷
1500	3 ¹⁶	1.5 ¹⁷	3 ¹⁷
2000	4 ¹⁶	2 ¹⁷	4 ¹⁷
5000	1 ¹⁷	5 ¹⁷	1 ¹⁸

* Denote exponent to the base 10.

TABLE 5. Percent Change in Reflectivity of Dielectric Material

n_o	$Nf = 10^{18}$					$Nf = 10^{19}$				
	$-100\overset{\circ}{\text{\AA}}$	$-50\overset{\circ}{\text{\AA}}$	λ_o	$+50\overset{\circ}{\text{\AA}}$	$+100\overset{\circ}{\text{\AA}}$	$-100\overset{\circ}{\text{\AA}}$	$-50\overset{\circ}{\text{\AA}}$	λ_o	$+50\overset{\circ}{\text{\AA}}$	$+100\overset{\circ}{\text{\AA}}$
$\lambda_o = 6700\overset{\circ}{\text{\AA}}$										
1.3	-2	-3	0	+3	+2	-22	-25	+11	+32	+25
1.5	-0.8	-2	0	+2	+0.8	-11.4	-13.5	+3	+15	+12
2.0	-0.7	-1	0	+1	+0.7	-3	-4	+1	+4	+3
$\lambda_o = 5400\overset{\circ}{\text{\AA}}$										
1.3	-1	-1.2	0	+1.8	+1.5	-11.4	-15	+3	+21	+12
1.5	-0.7	-0.8	0	+1	+0.9	-5.8	-7.5	+1	+8.5	+7
2.0	0	0	0	0	0	-1.8	-2	0	+2.5	+2
$\lambda_o = 4800\overset{\circ}{\text{\AA}}$										
1.3	-0.3	-1.3	0	+2	+1	-9	-10	+1.8	+15	+9.2
1.5	-0.2	-0.5	0	+0.8	+0.8	-4	-5	+0.5	+6	+4.2
2.0	0	0	0	0	0	-0.6	-1.8	0	+2	+1
$\lambda_o = 4000\overset{\circ}{\text{\AA}}$										
1.3	-0.1	-0.2	0	+0.5	+0.2	-4	-6.2	+0.5	+7	+5
1.5	0	0	0	0	0	-2	-2.5	0	+3	+2
2.0	0	0	0	0	0	-0.7	-1.2	0	+1.8	+0.7

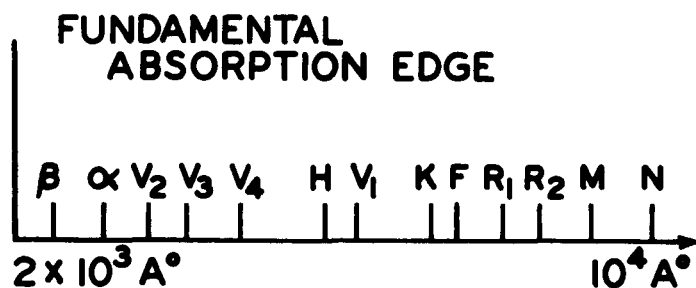


Fig. 1. APPROXIMATE SPECTRAL PEAKS. After J.H.O. Varley, J. Nucl. Energy I, 130 (1954)

Fig. 2. MODEL SCHEMES After Schulman and Compton (1962)

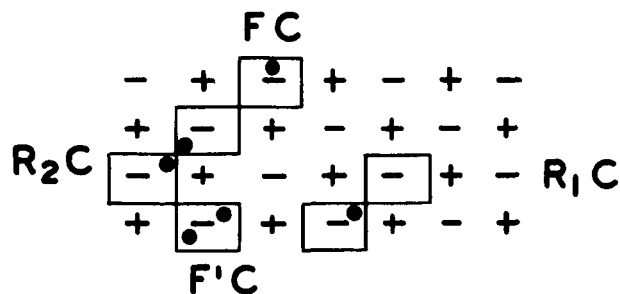
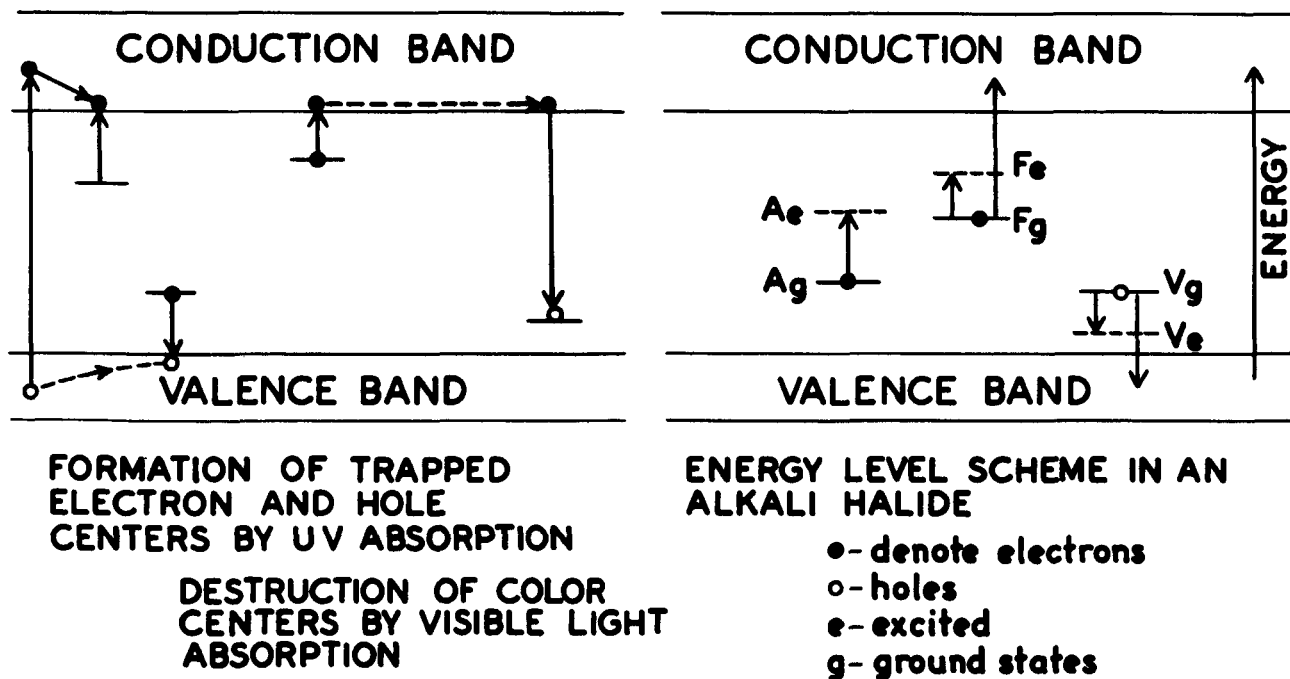


Fig. 3. SEITZ'S MODEL OF COLOR CENTERS

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